

Tau polarization measurements at the LHC in supersymmetric models with a long-lived stau

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Abstract

Supersymmetry (SUSY) with a long-lived stau is an attractive scenario in the LHC experiments because one can directly observe stau tracks in each SUSY event, and thus precise measurements of SUSY particle masses are possible. In this scenario, we discuss the possibility to observe/measure parity violation in interactions among SUSY particles. Such a measurement will be important in determining spins and chiralities of SUSY particles. We use the last step of the cascade-decay chain: $\chi^0 \rightarrow \tilde{\tau}\tau \rightarrow \tilde{\tau}(l\nu\bar{\nu})$, where the polarization of the tau lepton can be determined statistically by looking at the energy distribution of the final state lepton. Comparing with the theoretical formula of the neutralino differential decay width, one can extract the size of parity violation in the interaction vertices among the stau, the tau lepton and the neutralino. We perform a Monte Carlo simulation to see if the effect is visible at the LHC experiments.

1 Introduction

If supersymmetry (SUSY) is the solution to the hierarchy problem, the superpartners should weigh around a few hundred GeV to TeV energy range, which is accessible at the LHC experiments. The way to discover SUSY or to measure the properties of SUSY particles are quite different depending on the pattern of the superparticle spectrum. In particular, the property of the lightest SUSY particle (LSP) is important for the search strategies.

Motivated by an explanation of dark matter of the Universe, many collider studies of SUSY models have assumed the case with the LSP being the neutralino (admixture of the Higgsinos and the gauginos). In the neutralino LSP case, the final states of the SUSY events always contain invisible neutralinos, and one needs various measurements to be combined in order to determine sparticle masses. The situation drastically changes if one assumes that one of the charged sleptons is lighter than the lightest neutralino. Such a scenario is possible if the slepton is not absolutely stable. For example, the slepton can decay into a lepton and gravitino if kinematically allowed. In particular, the scalar tau lepton (stau) can easily be lighter than the neutralino in many SUSY models due to the quantum correction through the large Yukawa interaction.

If the life-time of the stau is longer than the time scale of the collider experiments (a few nsec), we will see charged tracks left by staus in each SUSY events, instead of the missing momentum in the neutralino LSP scenario. Methods to search for a long-lived charged particle in hadron colliders have been studied in Refs. [1, 2, 3, 4, 5]. Also, various advantages in studying SUSY models at the LHC have been reported. The stau momenta and velocities can be measured by analyzing the stau tracks, from which the stau mass can be extracted with a good accuracy [6, 7, 8]. The measurements of other sparticle masses [9, 10, 11, 12, 13, 14] and the spin measurement of the stau [15] have also been discussed. Methods to measure the stau life-time have been proposed in various contexts [16, 17, 18, 19, 20]. The chargino-neutralino production and subsequent decay processes at the LHC have been studied in Ref. [21] and the possibilities to observe parity/CP violations have been discussed.

In this paper, we discuss the possibility to measure the tau polarization in the neutralino decay, $\chi^0 \rightarrow \tilde{\tau}\tau$, where the neutralinos are mainly produced by the cascade decays of colored SUSY particles. The tau polarization carries information on whether the lightest stau is the partner of the right- or left-handed tau lepton, and also whether the decaying neutralino is

mainly composed of the gauginos or the Higgsinos. The polarization can be determined by looking at the energy distribution of the τ -decay product [22] due to the fact that the weak interaction maximally violates parity. We use the leptonic decay mode of the tau lepton, $\tau \rightarrow l\nu\bar{\nu}$, in this work. We first show the formula for the lepton-energy distribution in the neutralino decay, and by using it we fit the data from the Monte Carlo simulation. We find that the size of parity violation (the tau polarization) can be measured in a simple model where only one of the neutralinos contributes to the final state. In a more complicated case, where there are two neutralinos contribute to the same final state, we can correctly reproduce the signs of parity violation in each decay vertex.

2 Neutralino decay

In this section, we present the differential decay width of $\chi^0 \rightarrow \tilde{\tau}\tau \rightarrow \tilde{\tau}(l\bar{\nu}_l\nu_\tau)$ as a function of the lepton-energy fraction. The parity asymmetry of this decay process carries information on the chirality of the stau and the composition of the neutralino, *i.e.*, whether it is gaugino-like or Higgsino-like.

The measurement of the tau polarization has also been studied in the neutralino LSP case. The effects of the tau polarization in the di-tau invariant mass distribution in cascade decays were studied in Refs. [23, 24, 25]. Ref. [26] studied the p_T distribution of the softest τ -jets to extract the tau polarization in the co-annihilation region in the mSUGRA model. The tau polarization measurements at e^+e^- colliders were studied in the stau-pair productions in Refs. [27, 28, 29]. The measurements of CP violation at e^+e^- colliders were also studied in Refs. [30, 31, 32].

2.1 Decay width

The polarization information of the tau lepton is imprinted to the energy distribution of the lepton in the leptonic tau decay. We show in this subsection the formula for the distribution of the lepton-energy fraction in the neutralino decays.

The relevant interaction Lagrangian for the neutralino decay is

$$\mathcal{L} = \overline{\chi_i^0}(g_{Li}P_L + g_{Ri}P_R)\tau\tilde{\tau}^\dagger + \text{H.c.} \ , \quad (1)$$

where P_L and P_R are the chirality projection operators, and g_L and g_R are coupling constants. We will discuss the relation to the underlying model parameters in the next subsection. The tau lepton is polarized if there is parity violation, *i.e.*, $|g_L| \neq |g_R|$. The explicit calculation shows that the differential decay width of the process, $\chi_i^0 \rightarrow \tau \tilde{\tau} \rightarrow (l \bar{\nu}_l \nu_\tau) \tilde{\tau}$, is

$$\frac{d\Gamma(\chi_i^0 \rightarrow \tau \tilde{\tau} \rightarrow l \bar{\nu}_l \nu_\tau \tilde{\tau})}{\Gamma_{\text{lept}}} = \frac{1}{3}(1-z) \left[(5+5z-4z^2) - a_N^{(i)}(1+z-8z^2) \right] dz, \quad (2)$$

where Γ_{lept} is the partial decay width of the leptonic mode [22]. The variable z is the lepton-energy fraction:

$$z = \frac{E_l}{E_\tau}, \quad (3)$$

where the energy of the lepton and τ (E_l and E_τ) are those in the rest frame of χ^0 . The formula (2) is independent of the tau charge or the flavor of the final state lepton, *i.e.*, electron or muon. The parameter $a_N^{(i)}$ represents the tau polarization and it is expressed in terms of the Lagrangian parameters:

$$a_N^{(i)} = \frac{|g_{Li}|^2 - |g_{Ri}|^2}{|g_{Li}|^2 + |g_{Ri}|^2}. \quad (4)$$

The z distributions in Eq. (2) for $a_N = -1, 0, +1$ are shown in the left panel of Fig. 1. The value $a_N = -1(+1)$ corresponds to the decay into right (left) handed τ . The lepton tends to be emitted to the same direction of τ if $a_N = 1$ (left-handed τ).

2.2 Coupling constants and the model parameters

The coupling constants in Eq. (1) are expressed in terms of the neutralino- and the stau-mixing parameters as follows:

$$g_{Li} = \left(-\frac{g_1}{\sqrt{2}} \mathbf{O}_{i1} - \frac{g_2}{\sqrt{2}} \mathbf{O}_{i2} \right) \sin \theta_{\tilde{\tau}} - \frac{m_\tau}{v \cos \beta} \mathbf{O}_{i3} \cos \theta_{\tilde{\tau}}, \quad (5)$$

$$g_{Ri} = -\frac{m_\tau}{v \cos \beta} \mathbf{O}_{i3} \sin \theta_{\tilde{\tau}} + \sqrt{2} g_1 \mathbf{O}_{i1} \cos \theta_{\tilde{\tau}}. \quad (6)$$

where g_1 is the coupling constant of the $U(1)_Y$ gauge interaction, g_2 is that of $SU(2)_L$, $\tan \beta$ is the ratio of the two vacuum expectation values (VEV) of the Higgs fields and v is the

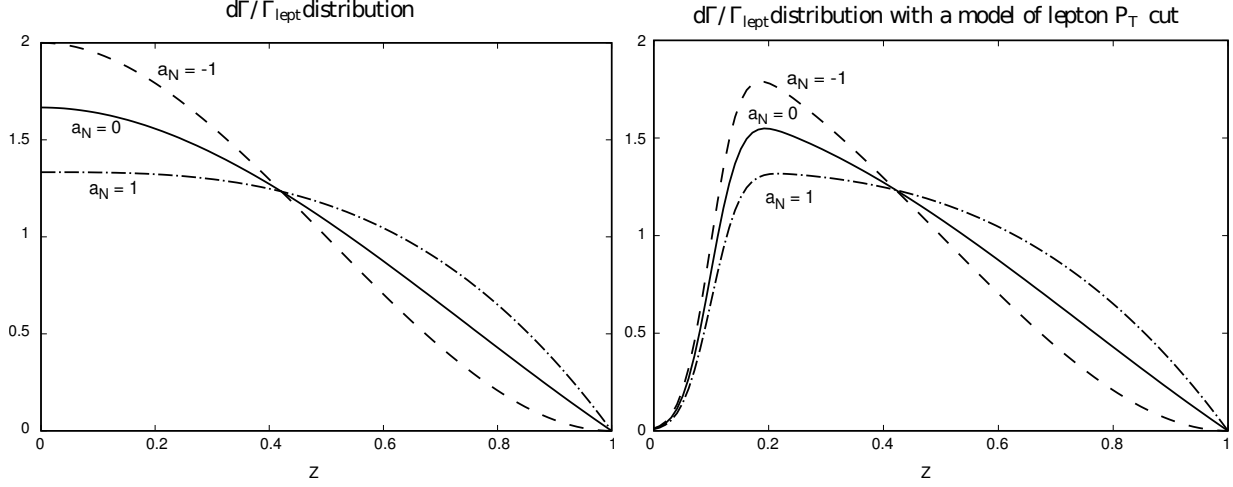


Figure 1: Distributions of the lepton-energy fraction ($z = E_l/E_\tau$) in the neutralino decay. The z dependence in Eq. (2) with $a_N = 0, \pm 1$ are shown in the left panel. The right panel is the same figure with a simple model to include the effects of the lepton p_T cut.

VEV of the Higgs field:

$$\tan \beta = \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}, \quad (7)$$

$$v^2 = \langle H_u^0 \rangle^2 + \langle H_d^0 \rangle^2. \quad (8)$$

The matrix elements \mathbf{O}_{ij} are those of a unitary matrix which diagonalizes the neutralino mass matrix,

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v}{\sqrt{2}} \cos \beta & \frac{g_1 v}{\sqrt{2}} \sin \beta \\ 0 & M_2 & \frac{g_2 v}{\sqrt{2}} \cos \beta & -\frac{g_2 v}{\sqrt{2}} \sin \beta \\ -\frac{g_1 v}{\sqrt{2}} \cos \beta & \frac{g_2 v}{\sqrt{2}} \cos \beta & 0 & -\mu \\ \frac{g_1 v}{\sqrt{2}} \sin \beta & -\frac{g_2 v}{\sqrt{2}} \sin \beta & -\mu & 0 \end{pmatrix}, \quad (9)$$

such that

$$\mathbf{O} M_{\chi^0} \mathbf{O}^T = M_{\chi^0}^{\text{diag}}. \quad (10)$$

The mixing angle of the stau is defined by

$$\tilde{\tau}_1 = \tilde{\tau}_L \sin \theta_{\tilde{\tau}} + \tilde{\tau}_R \cos \theta_{\tilde{\tau}}. \quad (11)$$

For example, let us consider the case in which the lightest neutralino (χ_1^0) and the lightest stau ($\tilde{\tau}_1$) are mainly the Bino and $\tilde{\tau}_R$, respectively, *i.e.*, $\cos\theta_{\tilde{\tau}} \simeq 1$ and $\mathbf{O}_{11} \gg \mathbf{O}_{12}, \mathbf{O}_{13}$. In this case, the largest contribution to the χ_1^0 decay is the second term in Eq. (6). Therefore, the parity violation parameter $a_N^{(1)}$ in Eq. (2) is $a_N^{(1)} \simeq -1$.

In the case where the decaying neutralino is mainly the Wino and the lightest stau is $\tilde{\tau}_R$, the situation is different. Since the pure Wino does not couple to the right-handed stau, the decay occurs either through the neutralino mixing or the stau mixing. In both cases, the parity violation is $a_N > 0$ in contrast to the previous example.

3 Monte Carlo simulation

In this section, we demonstrate by using a Monte Carlo simulation that the distribution obtained in the previous section is observable at the LHC experiments.

3.1 Basic set up

We generated events of SUSY particle productions at a pp collider at $\sqrt{s} = 14$ TeV (LHC) by using the HERWIG package [33]. We use CTEQ5L [34] for the parton distribution function. The TAUOLA package [35] is used for the τ decays and the events are passed through the AcerDET detector simulator [36] where the lepton momentum are smeared to simulate the detector effects.

The final state contains two stau tracks. The identification of those staus can be used to eliminate the background from the Standard Model processes. In order to distinguish staus from muons, we impose following selection cuts on the candidate stau tracks:

- $0.40 < \beta < 0.91$,
- $p_T > 10$ GeV ,
- $\eta < 2.4$.

Here and hereafter, we do not take into account the momentum and the velocity resolutions of the staus, *i.e.*, the parton level information is used. We assume in the following that the stau and neutralino masses are known. It has been reported in Refs. [7, 8, 9, 10, 11, 14] that those quantities are measurable with a good accuracy.

3.2 Lepton p_T cut and the deformation of the z distribution

We also require $p_T > 15$ GeV for the lepton momentum. This cut affects the shape of the z distribution in Eq. (2). We model the effect of the p_T cut in the z distribution by multiplying the following weight:

$$\frac{1}{2} \text{Erfc} \left(\frac{p_T^{\min} - Cz}{\sqrt{2}\sigma_{p_T}} \right) , \quad (12)$$

where p_T^{\min} is 15 GeV, and C and σ_{p_T} are parameters to be determined by fitting the data. We plot in the right panel of Fig. 1 the z distribution after multiplying this factor with $C = 150$ GeV and $\sigma_{p_T} = 6.0$ GeV.

3.3 Model I

We use the MSSM without flavor mixing and ignore the Yukawa interactions of the first and second generations. As the first example, we take a simple model in which only one of the neutralinos (χ^0) and one of the staus are significantly lighter than others, and the lightest neutralino and the lightest stau are almost the Bino and right-handed, respectively. The value of the parity violation parameter is

$$a_N = -0.99 , \quad (13)$$

in this case.

The MSSM parameters we take are listed in Tab. 1. We follow the convention of SUSY Les Houches Accord [37]. The χ^0 and $\tilde{\tau}$ masses are calculated to be

$$m_{\chi^0} = 195 \text{ GeV} , \quad m_{\tilde{\tau}} = 118 \text{ GeV} . \quad (14)$$

We used the ISAJET package [38] for the calculation of the mass spectrum and the branching ratios. We generate 10,000 SUSY events with the parameter set given in Tab. 1. The number of events corresponds to the integrated luminosity of 14.5 fb^{-1} .

The neutralinos are mainly produced by the cascade decays of the squarks and gluinos. The value of z (the lepton-energy fraction) in each candidate event can be calculated from the measured invariant mass of the lepton and the stau,

$$z = \frac{M_{\tilde{\tau}l}^2 - m_{\tilde{\tau}}^2}{m_{\chi^0}^2 - m_{\tilde{\tau}}^2} , \quad (15)$$

Parameter	Value
M_1	195.7 [GeV]
M_2	800.0 [GeV]
M_3	1003.7 [GeV]
$\tan \beta$	39.46
μ	800.0 [GeV]
B	694[GeV]
M_{Q_1}, M_{Q_2}	1400[GeV]
M_{L_1}, M_{L_2}	518[GeV]
M_{Q_3}	1241[GeV]
M_{L_3}	487[GeV]
M_{u^c}	1321[GeV]
M_{d^c}	1311[GeV]
M_{c^c}	1321[GeV]
M_{s^c}	1311[GeV]
M_{e^c}	278[GeV]
M_{μ^c}	277[GeV]
M_{b^c}	1210[GeV]
M_{t^c}	1075[GeV]
M_{τ^c}	160[GeV]
A_t	-503[GeV]
A_b	-567[GeV]
A_τ	-48.3[GeV]

Table 1: Parameters of Model I.

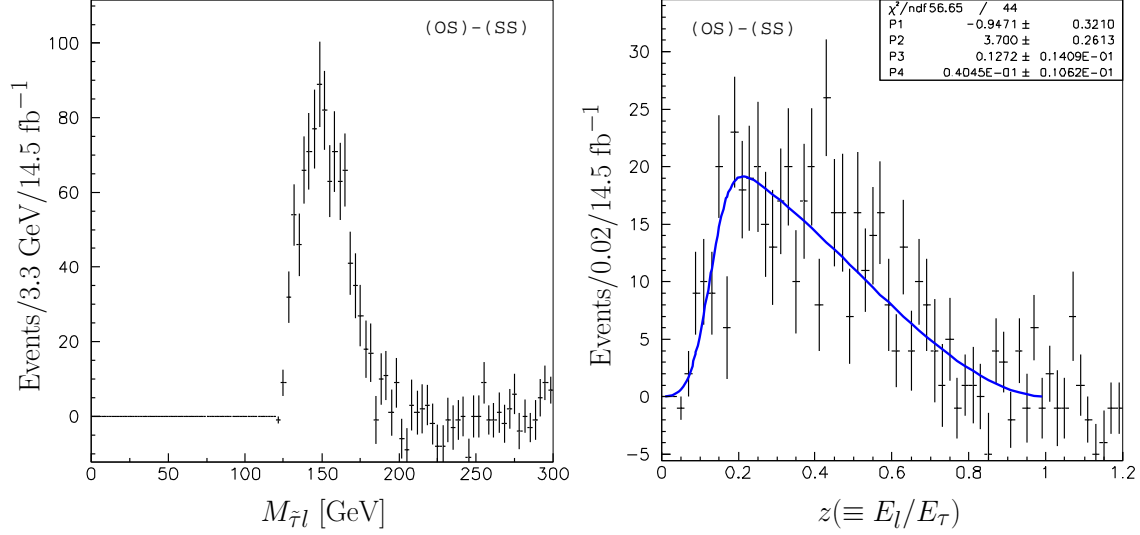


Figure 2: The histograms of the $\tilde{\tau}$ - l invariant mass (left) and z ($= E_l/E_\tau$) in Model I.

where $M_{\tilde{\tau}l}$ is

$$M_{\tilde{\tau}l}^2 = (p_{\tilde{\tau}} + p_l)^2 . \quad (16)$$

We show in Fig. 2 the histograms of the invariant mass (left) and the z parameter (right). In these plots, we select all possible combinations of a stau and a lepton with the opposite charges in each candidate event. In order to eliminate the contributions from wrong combinations and from background events such as leptons from W -boson decays, we subtract the same distributions calculated by using the combinations with the same signs [14]. After the selection cuts and the charge subtraction explained above, 978 events remained.

By fitting the z distribution in Fig. 2 with the function in Eq. (2) multiplied by a factor in Eq. (12), we obtain the a_N parameter to be:

$$a_N = -0.95 \pm 0.32 . \quad (17)$$

Comparing with the input value in Eq. (13), we can see that the parity violation is measured quite successfully.

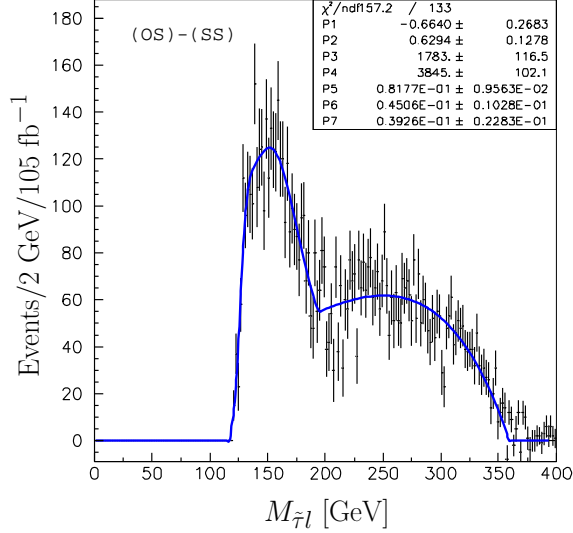


Figure 3: The histogram of the $\tilde{\tau}$ - l invariant mass in Model II.

3.4 Model II

As the second example, we take a model where the Wino-like neutralino is not so heavy compared to the Bino-like one as is so in the models motivated by the GUT relation of the gaugino masses. The model parameters are listed in Tab. 2. The neutralino and stau masses are

$$m_{\chi_1^0} = 195 \text{ GeV} , \quad m_{\chi_2^0} = 359 \text{ GeV} , \quad m_{\tilde{\tau}} = 118 \text{ GeV} . \quad (18)$$

The parity asymmetries $a_N^{(1)}$ and $a_N^{(2)}$ are calculated to be

$$a_N^{(1)} = -0.99 , \quad a_N^{(2)} = 1.0 . \quad (19)$$

Unlike the case of Model I, we cannot reconstruct z in the event-by-event basis since we do not know whether the decaying neutralino is χ_1^0 or χ_2^0 . Therefore, we need to directly fit the invariant mass distribution which contains events of both neutralinos.

We generated 90,000 SUSY events with this parameter set. The number of events corresponds to the integrated luminosity of 104.6 fb^{-1} . We show the invariant mass distributions (Fig. 3) using the same technique as we used for the Model I. After the cuts and the subtraction explained before, 7,677 events remained. We can see contributions from decays of two kinds of neutralinos.

Parameter	Value
M_1	195.7 [GeV]
M_2	363.9 [GeV]
M_3	1003.7 [GeV]
$\tan \beta$	39.46
μ	800.0[GeV]
B	694[GeV]
M_{Q_1}, M_{Q_2}	1400[GeV]
M_{L_1}, M_{L_2}	518[GeV]
M_{Q_3}	1241[GeV]
M_{L_3}	487[GeV]
M_{u^c}	1321[GeV]
M_{d^c}	1311[GeV]
M_{c^c}	1321[GeV]
M_{s^c}	1311[GeV]
M_{e^c}	278[GeV]
M_{μ^c}	277[GeV]
M_{b^c}	1210[GeV]
M_{t^c}	1075[GeV]
M_{τ^c}	160[GeV]
A_t	-504[GeV]
A_b	-567[GeV]
A_τ	-48.3[GeV]

Table 2: Parameters of Model II.

Before fitting the distribution in Fig. 3, we checked the validity of Eq. (2) combined with Eq. (12) for the Model II. We did it by separating the χ_1^0 and the χ_2^0 events by using information from the event generator and performed the fitting for each event set. Reasonable values for $a_N^{(1)}$ and $a_N^{(2)}$ are obtained:

$$a_N^{(1)} = -0.80 \pm 0.13, \quad a_N^{(2)} = 0.94 \pm 0.084. \quad (20)$$

For the fitting of the histogram in Fig. 3, we use the sum of two fitting functions corresponding to each neutralino:

$$\sum_{i=1,2} N_i \frac{d\Gamma_i(z_i)}{\Gamma_{\text{lept}}^{(i)}} \times \frac{1}{2} \text{Erfc} \left(\frac{p_T^{\min} - C_i z_i}{\sqrt{2}(\sigma_{p_T}^i)} \right), \quad (21)$$

where $p_T^{\min} = 15$ GeV, and $d\Gamma_i/\Gamma_{\text{lept}}^{(i)}$ is the function in Eq. (2). The energy fraction z_i is related to the $\tilde{\tau}$ - l invariant mass, $M_{\tilde{\tau}l}$, as

$$z_i = \frac{M_{\tilde{\tau}l}^2 - m_{\tilde{\tau}}^2}{m_{\chi_i^0}^2 - m_{\tilde{\tau}}^2}. \quad (22)$$

There are eight fitting parameters $a_N^{(i)}$, N_i , C_i and $\sigma_{p_T}^i$ for $i = 1, 2$ in the function.

Since it is difficult to find the best fit for such many parameters, we here make a (semi) theoretic assumption on a relationship between two parameters C_1 and C_2 in order to reduce the number of parameters. In Eq. (21), the combinations of $C_i z_i$ represent the average values of p_T^l from the χ_i^0 decay in the laboratory frame. Since the neutralinos are produced mainly from heavy colored particles, it is likely to be highly boosted and thus the tau lepton from the neutralino decay is pointing to the similar direction to the one of the neutralino in the laboratory frame. Therefore, there is an approximate relation:

$$\langle p_T^{\text{lept}} \rangle = z_i \langle p_T^\tau \rangle \simeq z_i \left\langle \frac{E_\tau}{E_{\chi_i^0}} \right\rangle \langle p_T^{\chi_i^0} \rangle, \quad (23)$$

where $\langle E_\tau/E_{\chi_i^0} \rangle$ is

$$\left\langle \frac{E_\tau}{E_{\chi_i^0}} \right\rangle = \frac{m_{\chi_i^0}^2 - m_{\tilde{\tau}}^2}{2m_{\chi_i^0}^2}. \quad (24)$$

The average transverse momentum of the neutralino, $\langle p_T^{\chi_i^0} \rangle$, is independent of the neutralino mass if it is highly boosted. Therefore, the ratio of C_1/C_2 is estimated to be

$$\frac{C_1}{C_2} = \frac{m_{\chi_2^0}^2 m_{\chi_1^0}^2 - m_\tau^2}{m_{\chi_1^0}^2 m_{\chi_2^0}^2 - m_\tau^2} . \quad (25)$$

By imposing the above relation, we could fit with the function in Eq. (21):

$$a_N^{(1)} = -0.66 \pm 0.27 , \quad a_N^{(2)} = 0.63 \pm 0.13 . \quad (26)$$

We obtain the correct signs for each parity violation although the magnitude of the parity violation is obtained to be smaller than the theoretical input values (-0.99 and 1.0 , respectively) due to our simple ansatz on the fitting function.

4 Summary

We studied the polarization measurement of the tau lepton at the LHC in the long-lived stau scenario. The polarization of the tau lepton from the neutralino decays carries information on whether the neutralino is Higgsino-like or gaugino-like and the chirality of the partner of the stau.

We have shown that the τ polarization can be measured by fitting the distribution of the lepton-energy fraction (E_l/E_τ) in the leptonic τ decays. We performed Monte Carlo simulations for two parameter sets of the MSSM. The first example we took is a simple case where the Bino-like neutralino is significantly lighter than others. In this case, we can directly fit the energy fraction by the theoretical function and the parity violation can be measured successfully.

In the second case where the Wino-like neutralino also contributes to the same final state, we fit the $\tilde{\tau}$ - l invariant mass distribution with the two contributions summed. Although the fitting gives a milder asymmetry compared to the theoretical inputs, we can obtain qualitatively correct features of parity violation in each neutralino decay.

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